



## What is claimed is:

1	1.	A method for reconstructing an image of a scattering medium, comprising:
2		directing energy into the scattering medium at a source location on the
3	scattering med	lium;
4		measuring the energy emerging from the scattering medium at a detector
5	location on the scattering medium;	
6		selecting an initial guess of internal properties of the scattering medium;
7	and the second s	predicting the energy emerging from the scattering medium using an
8	equation of rac	diative transfer, wherein the prediction is a function of the initial guess;
9		generating an objective function based on a comparison of the prediction
10	with the measurement;	
11		generating a gradient of the objective function by a method of adjoint
12	differentiation;	
13		modifying the initial guess of the properties of the scattering medium
14	based on the gradient of the objective function; and	
15		generating an image representation of the internal properties of the
16	scattering med	lium.

- 1 2. The method according to claim 1, further comprising repeating the
  2 predicting of the energy emerging from the scattering medium based on the modified
  3 initial guess, generating the objective function and modifying the initial guess, until at
- 4 least one of a predetermined number of repetitions has occurred and the objective
- 5 function reaches a predetermined threshold.

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- 1 3. The method according to claim 1, wherein the prediction depends on the boundary conditions.
- 1 4. The method according to claim 3, wherein the boundary conditions
  2 account for a refractive mismatch at an interface between the medium and at least one of
  3 the detectors and source.
- 1 5. The method according to claim 1, wherein the prediction comprises an 2 iterative process producing intermediate results.
- 1 6. The method according to claim 5, wherein the intermediate results of the prediction are stored.
- 7. The method according to claim 6, wherein generating the gradient of the objective function by adjoint differences uses the intermediate results of the prediction.
- 1 8. The method according to claim 7, wherein generating the gradient 2 comprises stepping backward through the intermediate results of the prediction.
- 1 9. The method according to claim 1, wherein the equation of radiative 2 transfer is time independent.
- 1 10. The method according to claim 9, wherein the time independent equation 2 of radiative transfer is:



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$$\omega \nabla \Psi(\mathbf{r}, \omega) + (\mu_a + \mu_s) \Psi(\mathbf{r}, \omega) = S(\mathbf{r}, \omega) + \mu_s \int_0^{2\pi} p(\omega, \omega') \Psi(\mathbf{r}, \omega') d\omega'$$

- where  $\Psi(\mathbf{r},\omega)$  is the radiance at the spatial position  $\mathbf{r}$  directed into a unit
- solid angle  $\omega$ , S(r,w) is the energy directed into the medium at spatial position r into a
- 6 unit solid angle  $\omega$ ,  $\mu_s$  is the scattering coefficient,  $\mu_a$  is the absorption coefficient and
- 7  $p(\omega, \omega')$  is the scattering phase function.
- 1 11. The method according to claim 10, wherein the scattering phase function
- 2 is:

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$$p(\cos\theta) = \frac{1 - g^2}{2(1 + g^2 - 2g\cos\theta)^{3/2}}$$

- 4 where  $\theta$  is the angle between the two unit solid angles  $\omega$  and  $\omega'$ , and g is
- 5 the anisotropy factor.
- 1 12. The method according to claim 1, wherein the equation of radiative
- 2 transfer is time dependent.
- 1 13. The method according to claim 12, wherein the time dependent equation
- 2 of radiative transfer is:

$$3 \frac{1}{c} \frac{\partial \Psi(r, \omega, t)}{\partial t} = S(r, \omega, t) - \omega \cdot \nabla \Psi(r, \omega, t) - (\mu_a + \mu_s) \Psi(r, \omega, t) + \mu_s \int_0^{2\pi} p(\omega, \omega') \Psi(r, \omega', t) d\omega'$$

- where  $\Psi(\mathbf{r}, \omega, t)$  is the radiance at the spatial position  $\mathbf{r}$  directed into a unit
- solid angle  $\omega$ , S(r,w, t) is the energy directed into the medium at spatial position r into a

- 7  $p(\omega,\omega')$  is the scattering phase function.
- 1 14. The method according to claim 13, wherein the scattering phase function

unit solid angle  $\omega$ ,  $\mu_s$  is the scattering coefficient,  $\mu_a$  is the absorption coefficient and

2 is:

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$$p(\cos\theta) = \frac{1 - g^2}{2(1 + g^2 - 2g\cos\theta)^{3/2}}$$

- where  $\theta$  is the angle between the two unit solid angles  $\omega$  and  $\omega'$ , and g is 4
- 5 the anisotropy factor.
- 15. 1 The method according to claim 1, wherein the properties include at least
- one of a scattering coefficient, an absorption coefficient, an anisotropy factor, and a 2
- 3 scattering phase function.
- 1 16. The method according to claim 1, wherein the objective function is a
- 2 normalized comparison of the predicted energy and the measured energy
- 1 17. The method according to claim 1, wherein the objective function is based
- 2 on the normalized sum of the differences between the predicted energy and the measured
- . 3 energy for each source detector pair, wherein a source detector pair is formed between
- 4 each source location and each detector location.
- 1 18. The method according to claim 1, wherein the objective function is:

$$\varphi = \frac{1}{2} \sum_{i}^{m} (P_i - M_i)^2$$

- where  $M_i$  represents the actual measurements and the  $P_i$  represents the
- 4 predicted measurements for each source defector pair i, m is the number of source
- 5 detector pairs, where a source detector pairs is formed between each source location and
- 6 each detector location.
- 1 19. The method according to claim 1, further comprising minimizing the
- 2 objective function.
- 1 20. The method according to claim 19, wherein minimizing the objective
- 2 function includes a one dimensional line search.
- 1 21. The method according to claim 20, wherein the one dimensional line
- 2 search is performed along a direction of the gradient of the objective function.
- 1 22. The method according to claim 20, wherein the one dimensional line
- 2 search is performed along a gradient-dependent direction.
- 1 23. The method according to claim 1, wherein the energy comprises near
- 2 infra-red energy.

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The method according to claim 1, wherein the scattering medium contains 1 24. regions wherein the scattering coefficients are not substantially greater than the 2 3 absorption coefficients. 1 25. The method according to claim 1, wherein the scattering medium contains a low scattering region embedded in a high scattering region. 2 The method according to claim 1, wherein the predicted energy is 1 26. 2 determined using finite element methods. The method according to claim 1, wherein the predicted energy is 27. 1 determined using finite difference methods. 2 A method for imaging the spatial optical properties of tissue, comprising: 28. 1 2 directing energy into the scattering medium at a source location on (a) 3 the tissue; measuring the energy emerging from the scattering medium at a 4 (b) detector location on the tissue; 5 selecting and initial guess of the spatial optical properties of the 6 (c) 7 tissue; predicting the energy emerging from the tissue using an equation 8 (d)

of radiative transfer in an iterative process, wherein the prediction is a function of the



10	initial guess and a refraction index mismatch at a boundary of the tissue, and the iterative				
11	process generates a plurality of intermediate predictions;				
12	(e) generating an objective function based on a normalized				
13	comparison of the prediction with the measured energy emerging from the scattering				
14	medium;				
15	(f) generating a gradient of the objective function by adjoint				
16	differentiation;				
17	(g) modifying the initial guess of the spatial properties of the tissue				
18	based on the gradient of the objective function;				
19	(h) repeating steps (d) through (g) until at least one of a threshold of				
20	modifications to the initial guess is reached and the objective function reaches a				
21	threshold; and				
22	(j) generating an image representation of the spatial optical properties				
23	of the tissue.				
1	29. A system for reconstructing an image of a scattering medium, comprising:				
2	a source for directing energy into the scattering medium at source location on the				
3	scattering medium;				
4	a detector for measuring the energy emerging from the scattering medium at a				
5	detector location on the scattering medium;				
6	an initial guess of internal properties of the scattering medium;				
7	means for predicting the energy emerging from the scattering medium using an				
8	equation of radiative transfer, wherein the prediction is a function of the initial guess;				



- 9 means for generating an objective function based on a comparison of the 10 prediction with the measurement; 11 means for generating a gradient of the objective function by a method of adjoint differentiation; 12 means for modifying the initial guess of the properties of the scattering medium 13 14 based on the gradient of the objective function; and means for generating an image representation of the internal properties of the 15 16 scattering medium.
- 30. The system according to claim 1, further comprising means for repeating 1 2 the predicting of the energy emerging from the scattering medium based on the modified 3 initial guess, generating the objective function and modifying the initial guess, until at 4 least one of a predetermined number of repetitions has occurred and the objective 5 function reaches a predetermined threshold.
- 31. The system according to claim 1, wherein the prediction depends on the 2 boundary conditions.
- 1 32. The system according to claim 31, wherein the boundary conditions 2 account for a refractive mismatch at an interface between the medium and at least one of 3 the detectors and source.

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- 1 33. The system according to claim 1, wherein the prediction comprises an
- 2 iterative process producing intermediate results.
- 1 34. The system according to claim 33, wherein the intermediate results of the
- 2 prediction are stored.
- 1 35. The system according to claim 34, wherein generating the gradient of the
- 2 objective function by adjoint differences uses the intermediate results of the prediction.
- 1 36. The system according to claim 35, wherein generating the gradient
- 2 comprises stepping backward through the intermediate results of the prediction.
- 1 37. The system according to claim 1, wherein the equation of radiative
- 2 transfer is time independent.
- 1 38. The system according to claim 37, wherein the time independent equation
- 2 of radiative transfer is:

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$$\omega \nabla \Psi(\mathbf{r}, \omega) + (\mu_a + \mu_s) \Psi(\mathbf{r}, \omega) = S(\mathbf{r}, \omega) + \mu_s \int_0^{2\pi} p(\omega, \omega') \Psi(\mathbf{r}, \omega') d\omega'$$

- where  $\Psi(\mathbf{r},\omega)$  is the radiance at the spatial position  $\mathbf{r}$  directed into a unit solid
- angle  $\omega$ , S(r,w) is the energy directed into the medium at spatial position r into a unit
- 6 solid angle  $\omega$ ,  $\mu_s$  is the scattering coefficient,  $\mu_a$  is the absorption coefficient and  $p(\omega, \omega')$
- 7 is the scattering phase function.

- 1 39. The system according to claim 38, wherein the scattering phase function
- 2 is:

3 
$$p(\cos\theta) = \frac{1 - g^2}{2(1 + g^2 - 2g\cos\theta)^{3/2}}$$

- 4 where  $\theta$  is the angle between the two unit solid angles  $\omega$  and  $\omega$ , and g is the
- 5 anisotropy factor.
- 1 40. The system according to claim 1, wherein the equation of radiative
- 2 transfer is time dependent.
- 1 41. The system according to claim 40, wherein the time dependent equation of
- 2 radiative transfer is:

$$3 \qquad \frac{1}{c} \frac{\partial \Psi(r,\omega,t)}{\partial t} = S(r,\omega,t) - \omega \cdot \nabla \Psi(r,\omega,t) - (\mu_a + \mu_s) \Psi(r,\omega,t) + \mu_s \int_0^{2\pi} p(\omega,\omega') \Psi(r,\omega',t) d\omega'$$

- where  $\Psi(\mathbf{r}, \omega, \mathbf{t})$  is the radiance at the spatial position  $\mathbf{r}$  directed into a unit solid
- 5 angle  $\omega$ , S(r,w, t) is the energy directed into the medium at spatial position r into a unit
- solid angle  $\omega$ ,  $\mu_s$  is the scattering coefficient,  $\mu_a$  is the absorption coefficient and  $p(\omega, \omega')$
- 7 is the scattering phase function.
- 1 42. The system according to claim 41, wherein the scattering phase function
- 2 is:

3 
$$p(\cos\theta) = \frac{1 - g^2}{2(1 + g^2 - 2g\cos\theta)^{3/2}}$$

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- where  $\theta$  is the angle between the two unit solid angles  $\omega$  and  $\omega'$ , and g is the
- 5 anisotropy factor.
- 1 43. The system according to claim 1, wherein the properties include at least
- 2 one of a scattering coefficient, an absorption coefficient, an anisotropy factor, and a
- 3 scattering phase function.
- 1 44. The system according to claim 1, wherein the objective function is a
- 2 normalized comparison of the predicted energy and the measured energy.
- 1 45. The system according to claim 1, wherein the objective function is based
- 2 on the normalized sum of the differences between the predicted energy and the measured
- 3 energy for each source detector pair, wherein a source detector pair is formed between
- 4 each source location and each detector location.
- 1 46. The system according to claim 1, wherein the objective function is:

$$\varphi = \frac{1}{2} \sum_{i}^{m} \left( P_i - M_i \right)^2$$

- where  $M_i$  represents the actual measurements and  $P_i$  represents the predicted
- 4 measurements for each source detector pair, m is the number of source detector pairs,
- 5 where a source detector pairs is formed between each source location and each detector
- 6 location.



- 1 47. The system according to claim 1, further comprising minimizing the
- 2 objective function.
- 1 48. The system according to claim 47, wherein minimizing the objective
- 2 function includes a one dimensional line search.
- 1 49. The system according to claim 48, wherein the one dimensional line
- 2 search is performed along a direction of the gradient of the objective function.
- 1 50. The system according to claim 49, wherein the one dimensional line
- 2 search is performed along a gradient-dependent direction.
- 1 51. The system according to claim 50, wherein the energy comprises near
- 2 infra-red energy.
- 1 52. The system according to claim 1, wherein the scattering medium contains
- 2 regions wherein the scattering coefficients are not substantially greater than the
- 3 absorption coefficients.
- 1 53. The system according to claim 1, wherein the scattering medium contains
- 2 a low scattering region embedded in a high scattering region.

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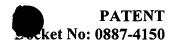
- 1 54. The system according to claim 1, wherein the predicted energy is 2 determined using finite element methods.
- 1 55. The system according to claim 1, wherein the predicted energy is 2 determined using finite difference methods.
- 1 56. A system for imaging the spatial distribution of optical properties of tissue, comprising:
- (a) a source for directing energy into the scattering medium at a source
   location on the tissue;
- 5 (b) a detector for measuring the energy emerging from the scattering medium 6 at a detector location on the tissue;
- 7 (c) an initial guess of spatial optical properties of the tissue;
- 8 (d) means for predicting the energy emerging from the tissue using an
  9 equation of radiative transfer in an iterative process, wherein the prediction is a function
  10 of the initial guess and a refraction index mismatch at a boundary of the tissue, and the
  11 iterative process generates a plurality of intermediate predictions;
  - (e) means for generating an objective function based on a normalized comparison of the prediction with the measured energy emerging from the scattering medium;
- 15 (f) means for generating a gradient of the objective function by adjoint 16 differentiation;



17	(g)	means for modifying the initial guess of the spatial properties of the tissue	
18	based on the gradient of the objective function;		
19	(h)	means for repeating steps (d) through (g) until at least one of a threshold	
20	of modificati	ons to the initial guess is reached and the objective function reaches a	
21	threshold; and		
22	(j)	means for generating an image representation of the spatial optical	
23	properties of the tissue.		
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1	57.	Computer executable software code stored on a computer readable	
2	medium, the code for reconstructing an image of a scattering medium, comprising:		
3		code to direct energy into the scattering medium at a source location on	
4	the scattering medium;		
5		code to measure the energy emerging from the scattering medium at a	
6	detector location on the scattering medium;		
7		code to receive an initial guess of internal properties of the scattering	
8	medium;		
9		code to predict the energy emerging from the scattering medium using an	
10	equation of ra	adiative transfer, wherein the prediction is a function of the initial guess;	
11		code to generate an objective function based on a comparison of the	
12	prediction with the measurement;		
13		code to generate a gradient of the objective function by a method of	
14	adjoint differ	rentiation;	

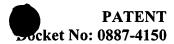


15	code to modify the initial guess of the properties of the scattering medium		
16	based on the gradient of the objective function; and		
17	code to generate an image representation of the internal properties of the		
18	scattering medium.		
1	58. Computer executable software code stored on a computer readable		
2	medium, the code for imaging the spatial distribution of optical properties of tissue		
3	comprising:		
4	(a) code to direct energy into the scattering medium at a source location on the		
5	tissue;		
6	(b) code to measure the energy emerging from the scattering medium at a detecto		
7	location on the tissue;		
8	(c) code to receive an initial guess of spatial optical properties of the tissue;		
9	(d) code to predict the energy emerging from the tissue using an equation of		
10	radiative transfer in an iterative process, wherein the prediction is a function of the initia		
11	guess and a refraction index mismatch at a boundary of the tissue, and the iterative		
12	process generates a plurality of intermediate predictions;		
13	(e) code to generate an objective function based on a normalized comparison of		
14	the prediction with the measured energy emerging from the scattering medium;		
15	(f) code to generate a gradient of the objective function by adjoint differentiation;		
16	(g) code to modify the initial guess of the spatial properties of the tissue based on		
17	the gradient of the objective function;		



18	(h) code to repeat steps (d) through (g) until at least one of a threshold of		
19	modifications to the initial guess is reached and the objective function reaches a		
20	threshold; and		
21	(j) code to generate an image representation of the spatial optical properties of the		
22	tissue.		
1	59. A computer readable medium having computer executable software code		
2	stored thereon, the code for reconstructing an image of a scattering medium, comprising:		
3	code to direct energy into the scattering medium at a source location on		
4	the scattering medium;		
5	code to measure the energy emerging from the scattering medium at a		
6	detector location on the scattering medium;		
7	code to receive an initial guess of internal properties of the scattering		
8	medium;		
9	code to predict the energy emerging from the scattering medium using an		
10	equation of radiative transfer, wherein the prediction is a function of the initial guess;		
11	code to generate an objective function based on a comparison of the		
12	prediction with the measurement;		
13	code to generate a gradient of the objective function by a method of		
14	adjoint differentiation;		
15	code to modify the initial guess of the properties of the scattering medium		
16	based on the gradient of the objective function; and		



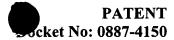


code to generate an image representation of the internal properties of the scattering medium.

1	60. A computer readable medium having computer executable software code
2	stored thereon, the code for imaging the spatial distribution of optical properties of tissue,
3	comprising:
4	(a) code to direct energy into the scattering medium at a source location on the
5	tissue;
6	(b) code to measure the energy emerging from the scattering medium at a detector
7	location on the tissue;
8	(c) code to receive an initial guess of spatial optical properties of the tissue;
9	(d) code to predict the energy emerging from the tissue using an equation of
10	radiative transfer in an iterative process, wherein the prediction is a function of the initial
11	guess and a refraction index mismatch at a boundary of the tissue, and the iterative
12	process generates a plurality of intermediate predictions;
13	(e) code to generate an objective function based on a normalized comparison of
14	the prediction with the measured energy emerging from the scattering medium;
15	(f) code to generate a gradient of the objective function by adjoint differentiation;
16	(g) code to modify the initial guess of the spatial properties of the tissue based on
17	the gradient of the objective function;
18	(h) code to repeat steps (d) through (g) until at least one of a threshold of
19	modifications to the initial guess is reached and the objective function reaches a

threshold; and





- 21 (j) code to generate an image representation of the spatial optical properties of the
- tissue.